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MEASUREMENT OF THE TOP QUARK MASS AND KINEMATIC PROPERTIES WITH THE DØ DETECTOR

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FOR THE DØ COLLABORATION

We review DØ's analysis of the top quark mass based on approximately $50\,\mathrm{pb}^{-1}$ of lepton + jets data. Preliminary results are presented on kinematic properties of these events, including a study of the two-dimensional distributions of reconstructed top mass vs. dijet mass. In addition, a preliminary mass analysis in the dilepton channels is presented.

1 Introduction

In March 1995, DØ reported the observation of the top quark, including a mass determination from the single lepton + jet (ℓj) channels[1]. Here, the ℓj mass analysis is reviewed, and preliminary results are presented on further kinematic analyses of these events plus a mass analysis from the dilepton channels.

2 Lepton + Jets Results

2.1 Mass Analysis

The ℓj mass analysis[1,2,3] is based on the published data sample ($\approx 50\,\mathrm{pb}^{-1}$) and event selection cuts, which are described elsewhere[1,4]. The 'loose' cuts are used, and we further require that each event have at least four 0.3-cone jets with $E_T > 15\,\mathrm{GeV}$ and $|\eta| < 2.5$. Only the four such jets with the highest E_T values are used in this analysis.

Besides the jets, we also measure for each event a lepton (e or μ) and missing E_T. If we assume that such an event is attributable to $t\bar{t}$ decay, there are three kinematic constraints: the invariant masses of the two W bosons and the constraint that the masses of the two t quarks should be equal. There is one unmeasured variable, which is the longitudinal component of the neutrino momentum. Thus, we can use a 2C kinematic fit to obtain the four-vectors (and thus the mass) of the t quarks. We also get a χ^2 from the fit, which indicates by how much the measured variables had to be pulled in order to satisfy the imposed constraints.

In order to do such a fit, however, we must identify each observed jet as being due to either one of the two b quarks from the t decays or one of the decay products of the hadronically decaying W boson. A fit is attempted for each of the 12 distinct ways of making this assignment. (But if the event has a tagged jet, only the 6 permutations which assign that jet as a b jet are considered.) The results are ranked by the χ^2 values, and those having $\chi^2 > 7$ are discarded. An average top mass is then computed from the three remaining fits with the smallest χ^2, with each fit weighted by $\exp\left(-\chi^2/2\right)$. This quantity will be called the *fitted mass*.

The fitted masses computed by this procedure are correlated with the true top mass, but they may be biased. In order to remove these biases and to take the background into account, we extract the final mass value using an unbinned maximum likelihood fit[2,5]. The parameters of the fit are the top mass m_t and the expected numbers of signal and background events, n_s and n_b. The expected distribution of fitted masses is determined as a function of the true top mass using Monte Carlo simulations. The expected number of background events is constrained to the value calculated from the counting experiment N_b to within its gaussian error.

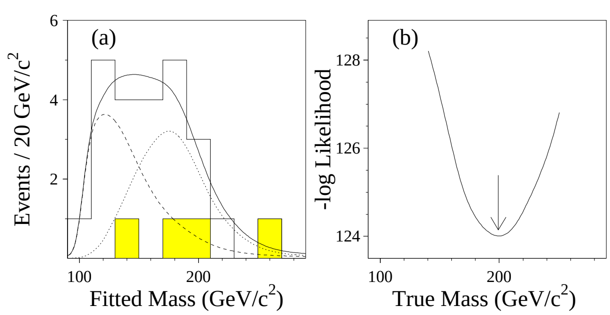

Figure 1: (a) Fitted masses for the ℓj data. Shaded entries indicate the location of the tagged events. The dashed and dotted curves show, respectively, the expected distribution for background and $t\bar{t}$ signal (using ISAJET with $m_t = 199\,\mathrm{GeV}/c^2$). The solid curve shows their sum. (b) $-\ln$ likelihood vs. top mass.

The results of analyzing the data are as follows. Of the 29 ℓj events passing the loose cuts, 27 have four jets, and 24 have at least one good fit. The fitted masses for these events are shown in Fig. 1(a). The estimated background to this sample is 11.6 ± 2.2 events, consisting of about 70% W + multijets (modeled using VECBOS) and 30% QCD fakes (modeled using multijet events containing an electromagnetic cluster). The expected top signal is modeled using ISAJET. The result of the likelihood fit is shown by the curves in Figs. 1(a) and (b). The best-fit values for the parameters are $m_t = 199^{+19}_{-21}(\text{stat.})\,\text{GeV}/c^2$, $n_b = 11.6^{+2.0}_{-2.0}$, and $n_s = 12.3^{+5.0}_{-4.2}$. The results of the fit do not change significantly if the gaussian constraint on the background is removed.

If, instead of ISAJET, we use HERWIG to model the top signal, the resulting top mass is about $4\,\text{GeV}/c^2$ lower, with about 20% smaller errors. The difference in errors is attributable to the fact that HERWIG predicts less gluon radiation than does ISAJET.

The largest contribution to the systematic error is the uncertainty in jet energy scale, which is estimated to be about 10%. This is propagated to the final result by taking an ensemble of 24-event Monte Carlo experiments with the observed signal/background ratio, scaling all the jets up or down by 10%, and performing a likelihood fit for each simulated experiment. This yields an estimated systematic error due to the jet scale of $^{+12}_{-20}\,\text{GeV}/c^2$.

Other systematic errors include the $\pm 4\,\text{GeV}/c^2$ difference observed between ISAJET and HERWIG, $\pm 4\,\text{GeV}/c^2$ from the likelihood fitting method, $\pm 2\,\text{GeV}/c^2$ from varying the QCD multijet background fraction, and $\pm 5\,\text{GeV}/c^2$ from the uncertainty in the background shape and other sources. Combining these gives a total systematic error of $^{+14}_{-21}\,\text{GeV}/c^2$, for a final result of $m_t(\ell j) = 199^{+19}_{-21}(\text{stat.})^{+14}_{-21}(\text{syst.})\,\text{GeV}/c^2$.

2.2 Kinematic Analysis

Armed with the results of the 2C fits, we can examine other kinematic properties of the t quarks. Two such quantities are the invariant mass of the $t\bar{t}$ pair and their average p_T. These quantities are plotted for the best χ^2 permutation for the ℓj data in Figs. 2(a) and (b). They are compared to the results expected from an appropriate mixture of ISAJET $t\bar{t}$ signal and background. No statistically significant differences are seen.

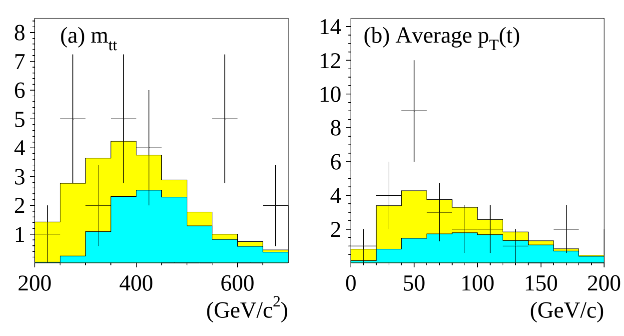

Figure 2: (a) Invariant mass and (b) average p_T of the $t\bar{t}$ pair in the 2C fit for the jet permutation with the best χ^2. The points are the loose data sample, the dark histogram is the expected $t\bar{t}$ signal (using ISAJET with $m_t = 200\,\text{GeV}/c^2$), and the light histogram is the expectation for signal + background.

2.3 Reconstructed Top vs. Dijet Mass Study

Each $t\bar{t} \to \ell +$jets event should contain a $W \to jj$ decay. It is interesting to ask if one can reconstruct a W mass peak for this decay from the data sample. Besides providing additional evidence that the sample contains top, this could in principle provide a method of directly calibrating the top mass against the known W mass. The 2C analysis described previously cannot be used for this due to the explicit W mass constraints which it imposes.

For this analysis[3], the four 0.5-cone jets with the largest E_T within $|\eta| < 2.5$ are used. The z-component of the neutrino momentum is determined by demanding $m(l\nu) = M_W$. This yields a quadratic; the solution with the smallest absolute value is used. Since no constraint is placed on the dijet masses, the only jet permutations we need to consider are the 4 different ways of partitioning the event into $(l\nu j)$ and (jjj) (only two if there is a tagged jet). For each such permutation, we plot a 'top mass' m_t against a dijet mass m_W. Each permutation is weighted by $\exp\left(-\chi^2/2\right)$, where $\chi^2 \propto \ln^2\left(m(l\nu j)/m(jjj)\right)$, and the normalization is chosen so that the weights for an event sum to unity. The quantity m_t is defined as a weighted average of $m(l\nu j)$ and $m(jjj)$ (50:50 for ej events and 40:60 for μj). The dijet mass m_W is defined as follows. If a jet in (jjj) is tagged, it is used as the b. Otherwise, the most energetic jet (in the top CM frame) is usually used as the b. In that case, m_W is the invariant mass of the other two jets. But if no jets in (jjj) are tagged and $(E_1 - E_2) < (E_2 - E_3)$ (again in the top CM frame), then the permutation is plotted twice, with equal weight, with both $m_W = m_{23}$ and $m_W = m_{13}$. Note that this procedure does *not* pull jet energies, and dijets are *not* selected for consistency with the W mass.

The result of this analysis on Monte Carlo samples is shown in Fig. 3 for both a HERWIG $t\bar{t}$ sample with $m_t = 200\,\text{GeV}/c^2$ and background. It is apparent that the top signal produces peaks near the expected locations along both axes. The shape of the background is rather different, with the peaks appearing lower. Fig. 4 shows the projections of the signal sample.

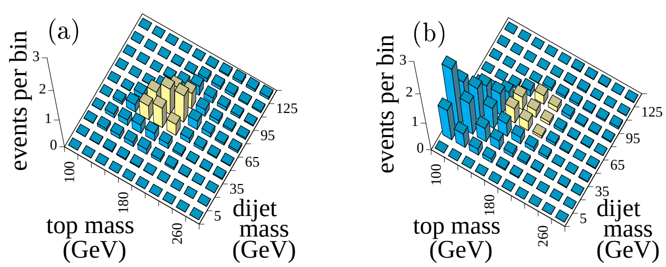

Figure 3: Reconstructed top mass vs. dijet mass for (a) HERWIG $t\bar{t}$ Monte Carlo with $m_t = 200\,\text{GeV}/c^2$, and (b) background.

The result for the ℓj data is shown in Fig. 5(a). This

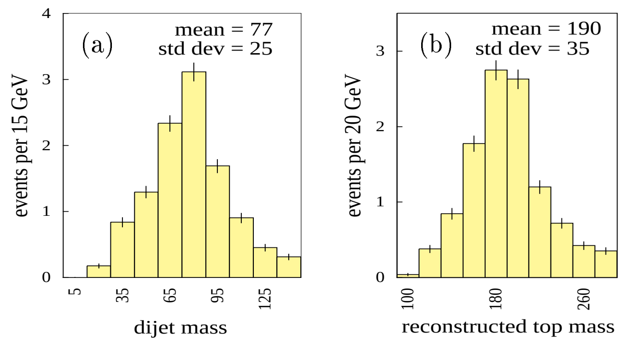

Figure 4: Projections of Fig. 3(a) along both axes.

can be compared with Fig. 5(b), which shows the expectation for a 200 GeV/c^2 top plus background. The shapes are similar, with the data showing contributions in both the signal and background regions. Projections of the data on both axes are shown in Fig. 6. Also shown are the same projections for the expected combination of signal and background, and for background alone. The data are seen to agree well with the expectations for a 200 GeV/c^2 top. The probability that the observed excess in the signal region of the m_t–m_W plane could be due to background has been found to be 1.3%[3].

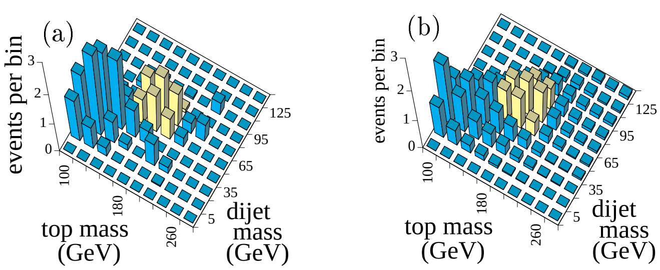

Figure 5: Reconstructed top mass vs. dijet mass for (a) ℓj data and (b) HERWIG $t\bar{t}$ Monte Carlo with $m_t = 200$ GeV/c^2 and background, mixed in the expected proportions.

3 Dilepton Mass Analysis

In addition to the ℓj channels, the dilepton ($\ell\ell$) channels also contain mass information. This section describes a *preliminary* mass analysis in these channels. Similar analyses have been described elsewhere[6].

This analysis uses a somewhat larger data sample than does the ℓj analysis ($\approx 72\,\mathrm{pb}^{-1}$). The selection cuts are the same as in the counting analysis[4]. There are five candidate events (1 ee, 2 $e\mu$, and 2 $\mu\mu$), with an estimated background of about 1 event. In each event, only the two highest E_T 0.5-cone jets are used.

Due to the fact that each event has two neutrinos, a dilepton event is underconstrained by one variable. Once the top mass has been specified, the kinematics of such

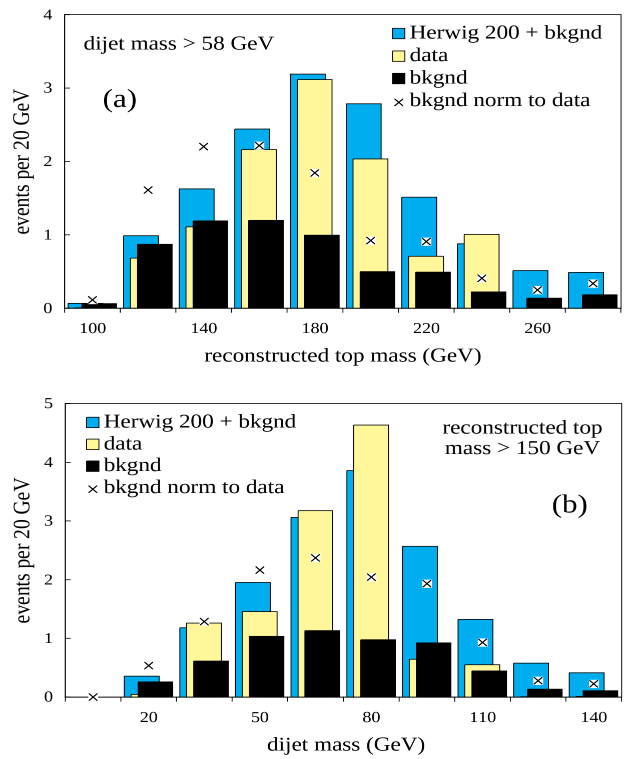

Figure 6: Projections of (a) reconstructed top mass m_t and (b) dijet mass m_{jj} with (a) $m_{jj} > 58$ GeV/c^2 and (b) $m_t > 150$ GeV/c^2, for ℓj data (light), sum of background and HERWIG 200 GeV/c^2 $t\bar{t}$ Monte Carlo (medium), background alone (black), and background normalized to match the data (X's).

an event can be completely determined, up to a possible four-fold ambiguity in the neutrino solutions (and presuming, for the moment, that we know which jet to associate with which lepton). Not all solutions are equally likely, however. We weight each solution i by the factor

$$w_i(m_t) = \mathcal{A}(m_t) f(x_i) f(\bar{x}_i) p(E^*(\ell)_i|m_t) p(E^*(\bar{\ell})_i|m_t), \quad (1)$$

where $f(x)$ is the proton structure function for valence quarks with momentum fraction x evaluated at $Q^2 = m_t^2$, $p(E^*(\ell)_i|m_t)$ is the probability distribution for the energy of the charged lepton in the rest frame of the t quark, and $\mathcal{A}(m_t)$ is a normalization factor chosen so that the average of the weights (over $t\bar{t}$ phase space) is constant with respect to m_t. The total weight $w(m_t)$ is then the sum over all possible neutrino solutions.

These weights define a likelihood curve as a function of m_t. To account for detector resolution, the measured parameters of the event are smeared many times with appropriate resolutions, and the resulting likelihoods are averaged. We also average over both possible jet assignments. The position of the peak of the resulting distribution, m_{peak}, is used as an estimate of the top mass.

The quantity m_{peak} so defined is analogous to the fitted mass from the ℓj analysis. In order to extract a mass value from a collection of events, we again use a maximum likelihood fit. The expected $t\bar{t}$ signal is modeled using the ISAJET Monte Carlo. The background consists of $Z \to \ell\ell'$, WW, and WZ processes, which are modeled using Monte Carlo, and fakes, which are modeled using data. This procedure has been tested on many simulated 5-event Monte Carlo experiments. The results for four different input top masses are shown in Fig. 7. The input masses are reproduced to within the available Monte Carlo statistics, and the widths are 25–35 GeV/c^2, depending on the input top mass.

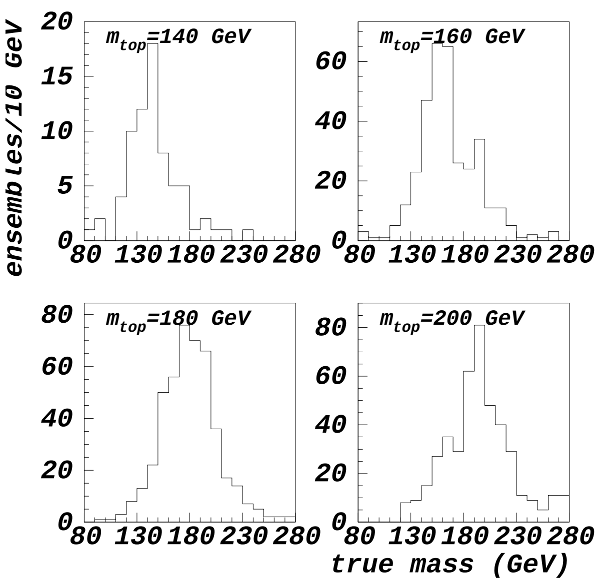

Figure 7: Distributions of the results of the likelihood fit for samples of five Monte Carlo events (1 ee, 2 $e\mu$, 2 $\mu\mu$).

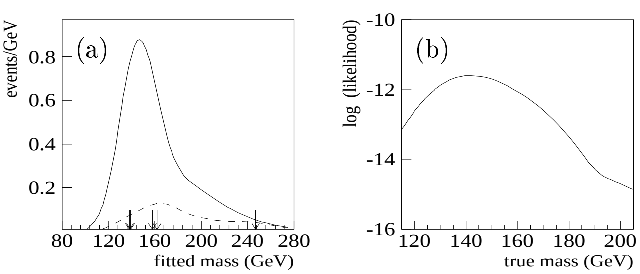

Figure 8: (a) Arrows show the m_{peak} values for the five dilepton candidates. The solid curve is the expected signal distribution for m_t equal to the maximum likelihood mass of 145 GeV/c^2, and the dashed curve is the background. (b) $-\ln$ likelihood vs. top mass.

The result of fitting the five candidates is shown in Figs. 8(a) and (b). The best-fit value for the top mass from these five events is about 145 GeV/c^2. The statistical error is estimated using the widths of the ensemble fit distributions in Fig. 7; this is $\sim$ 25 GeV/c^2 for a top mass of 145 GeV/c^2. The result is nearly unchanged if we use only the two events in the $e\mu$ channel (where the background is expected to be the smallest).

The dominant contributions to the systematic error are the uncertainty in the jet energy scale and the dependence on the Monte Carlo generator used. Other contributions include uncertainties in the determination of the expected signal and background distributions and the choice of the weight functions. The total systematic error is estimated to be ± 20 GeV/c^2, for a final result of $m_t(\ell\ell) \approx 145 \pm 25(\text{stat.}) \pm 20(\text{syst.})$ GeV/c^2.

4 Summary and Conclusions

The published result from the ℓj channels is

$$m_t(\ell j) = 199^{+19}_{-21}(\text{stat.})^{+14}_{-21}(\text{syst.})\,\text{GeV}/c^2.$$

The errors are based on ISAJET and allow for the differences between ISAJET and HERWIG.

A preliminary analysis of the reconstructed top vs. dijet mass has been presented. With 98.7% confidence, we observe a peak in the top mass – dijet mass plane. The peak and its projections are similar to that expected from our mixture of $t\bar{t}$ signal and background.

A preliminary mass analysis of the dilepton candidates has also been presented. This gives a result of

$$m_t(\ell\ell) \approx 145 \pm 25(\text{stat.}) \pm 20(\text{syst.})\,\text{GeV}/c^2.$$

With these errors, the difference between this result and the ℓj result is not statistically significant. We do not give a combined mass value pending further understanding of the correlated systematics between channels. Furthermore, note that these two analyses are sensitive to somewhat different effects. The ℓj analysis is more sensitive to complications from initial and final state gluon radiation, but does not make assumptions about the $t\bar{t}$ production and decay dynamics. The $\ell\ell$ analysis is less sensitive to QCD radiative effects, but does make assumptions about the dynamics.

Work is continuing on all fitting methods to better understand the systematic effects which influence them.

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